Liquid Argon Detector
Developments in the U.S.

Mitch Soderberg
on behalf of many colleagues in the U.S. and abroad
NNN 2013
• Liquid Argon Time Projection Chambers (LArTPCs) are imaging detectors that offer exceptional capabilities for studying neutrinos.

• In this workshop you’ve heard about pioneering work done by ICARUS, and you’ve just heard about physics potential of this technology.

• I will give an overview of recent LArTPC activities in the U.S., focusing mainly on technical developments, which has become a very daunting task due to the wide array of projects underway.
Before I Start...

It seems to be something of a tradition at NNN to have a talk that summarizes LArTPC work in the U.S. and elsewhere.

NNN 08: Paris, France

**Liquid Argon in the U.S.**

- **Materials Test Stand**
- **Bo**
- **Yale Tracks**
- **ArgoNeuT**
- **MicroBooNE**

**Rapid progress in LArTPC development**

NNN 10: Toyama, Japan

**LArTPC Work at Fermilab**

- **Materials/Electronics Test Stand**
- **UCLA/Pisa Long-Drift Test at CERN**
- **L.A.P.D.**
- **ArgoNeuT**
- **MicroBooNE**

Our ideas continue to evolve, and enthusiasm for this combination of physics and technology only seems to grow.
An opinion, since this is a workshop...

In the past ~2 years in the U.S. we seem (to me at least) to have crossed a “tipping point” where the idea that massive, kiloton-scale LArTPCs are technically possible has become accepted within the community.
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Even if we are entering the “Snowball” region and gaining momentum towards large detectors, there is still a LOT of development of hardware/software/physics that needs to happen. The U.S.-based activities I will describe in this talk will help push us further in the right direction.
- Ionization produced in neutrino interactions is drifted along E-field to finely segmented wireplanes.
- Timing of wire pulse information is combined with known drift speed to determine drift-direction coordinate.
- Calorimetry information is extracted from wire pulse characteristics.
- Abundant scintillation light, which LAr is transparent to, also available for collection and triggering.

Refs:
Neutrino Interaction in ArgoNeuT

Pixel size: 4mm x 0.3mm

Color is proportional to amount of charge collected

Drift Coordinate

~96cm

Drift Coordinate

un/7cm

un/7cm
Why Noble Liquids for Neutrinos?

- Abundant ionization electrons and scintillation light can both be used for detection.
- If liquids are highly purified (<0.1ppb), ionization can be drifted over long distances.
- Excellent dielectric properties accommodate very large voltages.
- Noble liquids are dense, so they make a good target for neutrinos.
- Argon is relatively cheap and easy to obtain (1% of atmosphere).
- Drawbacks?...no free protons...nuclear effects.

<table>
<thead>
<tr>
<th></th>
<th>He</th>
<th>Ne</th>
<th>Ar</th>
<th>Kr</th>
<th>Xe</th>
<th>Water</th>
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<tbody>
<tr>
<td>Boiling Point [K] @ 1atm</td>
<td>4.2</td>
<td>27.1</td>
<td>87.3</td>
<td>120.0</td>
<td>165.0</td>
<td>373</td>
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<tr>
<td>Density [g/cm(^3)]</td>
<td>0.125</td>
<td>1.2</td>
<td>1.4</td>
<td>2.4</td>
<td>3.0</td>
<td>1</td>
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<td>Radiation Length [cm]</td>
<td>755.2</td>
<td>24.0</td>
<td>14.0</td>
<td>4.9</td>
<td>2.8</td>
<td>36.1</td>
</tr>
<tr>
<td>dE/dx [MeV/cm]</td>
<td>0.24</td>
<td>1.4</td>
<td>2.1</td>
<td>3.0</td>
<td>3.8</td>
<td>1.9</td>
</tr>
<tr>
<td>Scintillation [(\gamma/\text{MeV})]</td>
<td>19,000</td>
<td>30,000</td>
<td>40,000</td>
<td>25,000</td>
<td>42,000</td>
<td></td>
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<tr>
<td>Scintillation (\lambda) [nm]</td>
<td>80</td>
<td>78</td>
<td>128</td>
<td>150</td>
<td>175</td>
<td></td>
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</tbody>
</table>
Technical Considerations for LArTPCs

- Purity: relying on Trigon “getters” and molecular sieve coupled with continuous recirculation and clean materials.

- Wires vs. “GEMs”: U.S. doesn’t seem to have focused on GEMs very much.

- Electronics: cold electronics for better S/N; multiplexing; etc...

- Light collection: lots of new and interesting ideas being pursued (PMTs, lightguides, etc...)

- High Voltage: How to test system before starting operations; Do we understand physics of HV in ultraclean LAr?

- Cryogenics and recirculation scheme: major cost drivers. Is there ground to gain here?

- Calibration: dedicated test-beam exposures, UV lasers, flashers, etc...

- Supply of many kilotons of LAr: Where do you buy many kilotons of LAr?

- Reconstruction/Software: Need to develop tools, preferably automated, that take full advantage of the TPC event images and light collection information. Need to be able to keep up with flood of raw data.
**LAr Worldwide**

Completed/Ongoing/Potential/Proposed/Suggested LAr Projects, separated by location of the detectors.

### **US**
- Materials Test Stand
- ArgoNeuT
- Liquid Argon Purity Demonstrator
- MicroBooNE
- LBNE
- 1 kTon LArTPC
- Test-Beam @ FNAL (LArIAT)
- Test-Beam @ Los Alamos (CAPTAIN)
- GLADE
- RADAR

### **Europe**
- 3-ton prototype
- 50-liter @ CERN
- 10m³
- ICARUS
- LArTPC in B-Field
- LANDD @ CERN
- ArgonTube @ Bern
- UV Laser
- GLACIER/LAGUNA
- Double-LAr @ CERN-PS

### **Japan**
- Test-Beam (T32) at J-PARC
- 100 kTon @ Okinoshima island

Message is that majority of these ideas are <5 years old, demonstrating growing interest.

*LAr also pursued for Dark Matter: DarkSide, ArDM, DEAP/CLEAN, WARP, Depleted Argon, ...*
The ArgoNeuT Project

- ArgoNeuT deployed a ~175 liter LArTPC in Fermilab NuMI neutrino beam.
- Located upstream of MINOS near detector, which provides muon reconstruction and sign selection.
- Collected $1.35 \times 10^{20}$ Protons on Target (POT), predominantly in antineutrino mode.

NuMI Beam at Fermilab

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Cryostat Volume</td>
<td>500 Liters</td>
</tr>
<tr>
<td>TPC Volume</td>
<td>175 Liters (90cm x 40cm x 47.5cm)</td>
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<tr>
<td># Electronic Channels</td>
<td>480</td>
</tr>
<tr>
<td>Electronics Style (Temp.)</td>
<td>JFET (293 K)</td>
</tr>
<tr>
<td>Wire Pitch (Plane Separation)</td>
<td>4 mm (4 mm)</td>
</tr>
<tr>
<td>Electric Field</td>
<td>500 V/cm</td>
</tr>
<tr>
<td>Max. Drift Length (Time)</td>
<td>0.5 m (330 μs)</td>
</tr>
<tr>
<td>Wire Properties</td>
<td>0.15mm diameter BeCu</td>
</tr>
</tbody>
</table>

Refs:
1.) The ArgoNeuT detector in the NuMI low-energy beam line at Fermilab, C. Anderson et al., JINST 7 P10019, Oct. 2012, arXiv:1205.6747
ArgoNeuT: Physics

• ArgoNeuT has highlighted need to consider nuclear effects (e.g. - Multinucleon Correlations, final-state activity) when analyzing LArTPCs.
• Repeat of CC-Inclusive analysis (shown at previous NNNs) in antineutrino mode.
• Papers in progress.

1.) Exclusive Topologies reconstruction in LAr-TPC experiments: a Novel Approach for precise Neutrino-Nucleus Cross-Sections Measurements, O. Palamara, K. Partyka, F. Cavanna, arXiv:1309.7480
2.) New Results from ArgoNeuT, T. Yang, NuFACT2013, hep-ex/1311.2096
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![Graphs and plots showing distributions of proton multiplicity for various particle species and comparison with data and models.](Image)

**Figure 3.** Distributions of proton multiplicity for various particle species and comparison with data and models.

**Figure 2.** Momenta versus true quantities for simulated event selection.

**Figure 1.** Comparison of data and models for various particle species.

**Figure 0.** Anti-neutrino mode run and preliminary analysis.

Ref:
2) New Results from ArgoNeuT, T. Yang, NuFACT2013, hep-ex/1311.2096
MicroBooNE will operate in the Booster neutrino beam at Fermilab starting in 2014. Combines physics with hardware R&D necessary for the evolution of LArTPCs.

- MiniBooNE low-energy excess
- Low-Energy (<1 GeV) neutrino cross-sections
- Cold Electronics (preamplifiers in liquid)
- Long drift (2.5m)
- Purity without evacuation.

Refs:
1.) Proposal for a New Experiment Using the Booster and NuMI Neutrino Beamlines, H. Chen et al., FERMILAB-PROPOSAL-0974
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<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Cryostat Volume</td>
<td>150 Tons</td>
</tr>
<tr>
<td>TPC Volume (l x w x h)</td>
<td>89 Tons (10.4m x 2.5m x 2.3m)</td>
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<tr>
<td># Electronic Channels</td>
<td>8256</td>
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<tr>
<td>Electronics Style (Temp.)</td>
<td>CMOS (87 K)</td>
</tr>
<tr>
<td>Wire Pitch (Plane Separation)</td>
<td>3 mm (3mm)</td>
</tr>
<tr>
<td>Max. Drift Length (Time)</td>
<td>2.5m (1.5ms)</td>
</tr>
<tr>
<td>Wire Properties</td>
<td>0.15mm diameter SS, Cu/Au plated</td>
</tr>
<tr>
<td>Light Collection</td>
<td>30 8” Hamamatsu PMTs</td>
</tr>
</tbody>
</table>
**MicroBooNE: Cold Electronics**

- CMOS preamplifiers located in liquid, attached to TPC, to minimize noise.
- 12-bit ADCs sampled at 2MHz (i.e. - 500ns per sample) for 4.8ms (x3 drift window).
- Several hour data buffering for Supernova analysis (triggered by receipt of alert signal from SNEWS).

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**Cold MotherBoards**

- Single Vessel Cryostat with 8-10% Ullage Foam Insulation
- 8256 TPC channels
- 30 PMT channels

**LAr**

- Decoupling and Wire Bias
- CMOS Analog Front End ASIC in LAr @ ~90K
- Warm Feedthrough

**GAr**

- Warm Flange 2x8 + 2x7 rows pin carriers 32 readout channels/row
- Intermediate Amplifier Line Driver
- Faraday Cage Extension

**DAQ in Detector Hall**

- TPC Readout Board
- Digitizing Section
- Data Handling Section
- On Board Memory
- Transmit Module
- Optical Transmitter
- Backplane
- Optical Link
- To DAQ PC

- PMT Readout Board
- Digitizing Section
- Data Handling Section
- On Board Memory
- Transmit Module
- Optical Transmitter
- Backplane
- Optical Link
- To DAQ PC

**Trigger Board**

- Beam Gate

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**References:**


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**Heat dissipation of 5 mW/channel**
MicroBooNE: Light Collection

- 30 8” Hamamatsu (R5912-02mod) cryogenic PMTs facing into the TPC volume.
- Tetraphenyl Butadiene coated plate in front of PMT to shift wavelength of UV scintillation light.
- PMTs are essential in disentangling out-of-time cosmic tracks from in-time neutrino interactions.

PMT System Installed in Cryostat (Sept. 2013).

Plate (that will be) coated with wavelength shifter

PMT Assembly

Refs:
1.) Testing of Cryogenic Photomultiplier Tubes for the MicroBooNE Experiment, T. Briese et al., hep-ex/1304.0821
MicroBooNE: Status

- Will move sealed-up detector over to new LArTF enclosure in early 2014.
- Commissioning begins in summer of 2014.
- Cryogenic recirculation system already being installed and tested prior to arrival of cryostat.

Rendering of cryostat + “hair” in LArTF

Liquid Argon Test Facility (LArTF)
LBNE pursuing membrane cryostats, using experience from industry.
Currently building 35-ton membrane cryostat to demonstrate liquid purity without initial evacuation as has previously been demonstrated by Liquid Argon Purity Demonstrator (LAPD) in a “traditional” cryostat.
• Argon gas acts like a piston, pushing atmosphere up and out of cryostat.
• Gas is cycled through cryostat until desired Oxygen concentration is reached.
• LAPD has routinely achieved LAr lifetimes >3 ms, (LBNE/MicroBooNE require ~1.5 ms)

Refs:
1) LAPD Update, B. Rebel, 2012 Fermilab PAC Meeting
LArIAT

- Dedicated test-beam exposure of LArTPC to charged-particles in appropriate energy regime will provide invaluable calibration information to feed into simulations.

- Liquid Argon In A Testbeam (LArIAT) experiment envisions two phases of running...initially with a small ArgoNeuT-sized detector (starting 2014), followed by a larger MicroBooNE scale detector.

![Modified ArgoNeuT Cryostat](image)
Coupling a 1-kiloton “far detector” (LAr1) with existing MicroBooNE experiment would create fantastic short-baseline neutrino program at Fermilab.

First phase is to install “near detector” (LAr1-ND) in vacant SciBooNE enclosure. Active volume of ~75 tons.

Leverage LBNE design work; provide beam test of the hardware.
All of this technology development culminates in the multi-kiloton LBNE far-detector, which will use a LArTPC to search for CP violation, proton decay, supernova neutrinos, etc...

Detector will be located underground at 4850 ft. level in the Sanford Underground Research Facility (SURF), in the path of an intense beam originating at Fermilab.

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<tbody>
<tr>
<td>Cryostat Volume</td>
<td>9400 tons (x2 = 18600 tons)</td>
</tr>
<tr>
<td>TPC Volume (l x w x h)</td>
<td>5000 tons (x2 = 10000 tons)</td>
</tr>
<tr>
<td># Electronic Channels</td>
<td>~150k/cryostat (x2 = ~300k)</td>
</tr>
<tr>
<td>Electronics Style (Temp.)</td>
<td>CMOS (87 K)</td>
</tr>
<tr>
<td>Wire Pitch</td>
<td>~5 mm</td>
</tr>
<tr>
<td>Max. Drift Length (Time)</td>
<td>2.3m (1.4ms)</td>
</tr>
<tr>
<td>Light Collection</td>
<td>Acrylic bars with TPB</td>
</tr>
</tbody>
</table>
The cryogenics systems consist of three kW liquid nitrogen liquefaction plants, a liquid stainless steel inner membrane supported by the hull. This construction gives a completely non-insulating design. Large LNG tanker ships are constructed using thick foam insulation and a thin 7–10 mm wall. Similar requirements and geometries are adapted in the adaptation of industrial LNG regasification plants.

- Two separate membrane cryostats each with 9.4 kiloton volume.
- TPC is formed by alternating rows of cathode (CPAs) and anode (APAs) assemblies that are hung from the ceiling of the cryostat.
• APAs are formed by wrapping angled wires around perimeter of frame. This allows readout all to come off the ends of the assembly, and helps to control the channel count.

• Light detection systems could be placed inside the APAs, minimizing their impact on active volume of LAr.
Software

• Extracting physics results from LArTPC data presents its own challenges that must be overcome and will require significant effort.

• Developing generators, simulation, reconstruction, etc... that fully encapsulate neutrino interactions in a LArTPC is a challenge that (in my opinion) rivals the hardware development. Deserves more attention than I’m giving it here.

• LArSoft framework is an attempt to share effort amongst experiments by developing common language and tools for analyzing LArTPCs.

Refs:
1.) https://cdcvs.fnal.gov/redmine/projects/larsoftsvn/wiki

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure.png}
\end{figure}
Conclusions

- LArTPCs are powerful detectors for studying neutrinos.
- Tremendous progress in recent years in U.S. efforts to develop this technology. Growing interest, which is good since there is lots of work to be done.
- My apologies to activities I didn’t have time to cover at all (Materials Test Stand, CAPTAIN, Light-Collection R&D, Long-Bo in LAPD, ...others).
- Next few years should be very exciting as experiments come online, and as development of kiloton-scale experiments continues.
Back-Up Slides
• First Results: Using 2 weeks of neutrino-mode data ($8.5 \times 10^{18}$ POT), the differential cross-section for inclusive charged-current muon neutrino production was measured.

• Analysis Selection:
  - Track originating within ArgoNeuT fiducial region.
  - Match to corresponding track in MINOS near detector.
  - MINOS track is negatively charged.

\[
\frac{\partial \sigma(u_i)}{\partial u} = \frac{N_{\text{measured},i} - N_{\text{background},i}}{\Delta u_i \epsilon_i N_{\text{targ}} \Phi
\]

Refs: